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Effect of alternate metals for use in natural fibre reinforced fibre metal laminates under bending, impact and axial loadings

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Abstract

Fibre Metal Laminate (FML) is largely used in the manufacture of aircrafts. The commercially available FMLs, GLARE, CARALL (CArbon Reinforced ALuminium Laminate) and ARALL make use of Aluminium metal. Other FMLs that are under study by researchers make use of metals such as Titanium and Magnesium based alloys. Owing to the high cost of carbon fibre and the necessity for environment friendly alternatives, in the present work, a portion of carbon is replaced by natural fibre jute in CARALL and CARMAL (CArbon Reinforced MAgnesium Laminate). To the knowledge of the authors, this attempt has not been made before in the field of FMLs. The resulting CArbon-Jute Reinforced ALuminium Laminate and CArbon-Jute Reinforced MAgnesium Laminate are named as CAJRALL and CAJRMAL. Both these laminates are made by hand layup technique and then compressed in a compression moulding machine. The CAJRALL and the CAJRMAL specimens are subjected to Axial, Flexure and Impact tests according to ASTM standards. The effect of the orientations of fibres and influence of the stacking sequences of the fibre and metal combinations and the use of alternating metals on the mechanical performance, are experimentally investigated. The experimental and theoretical results as well as the results obtained through Finite Element Analysis are found to be in close agreement. Also the failure of the FML is predicted by conducting micro level structure analysis.

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Keywords: Fibre Metal Laminate (FML); Jute; CAJRALL; CAJRMAL; Mechanical behaviour

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1. Introduction

After World war-II, plenty of changes have taken place in the area of material research. Owing to the process of depletion of traditional metals, such as steel, cast iron, aluminium, zinc, copper, magnesium, titanium and their alloys, new technologies are being evolved by material and design engineers, by inventing a new category of materials named composites, which are formed by combining different metals. Even though the purpose of the invention of the composite was different, it turned out to be a welcome move, as it resulted in a low weight material. Later on, several ideas were developed to create composites with much lower density, using fibres such as carbon and glass instead of the conventional metals. Even though, carbon and glass possessing high strength were able to replace the conventional metals, the world welcomed natural fibres in the sphere of composites [1], as they are safe unlike synthetic fibres which cause health hazards and help to create a green environment.

Today, materials research is moving towards natural fibre composites/laminates. It is because of factors such as low weight, cost effectiveness, man's desire to go in for natural products, environment friendliness, renewable nature, biodegradability with respect to fibre, and ready use of plants / trees with less processing. The natural fiber-containing composites, possessing noticeable properties on par with man-made fibres, are used in transportation (automobiles, railway coaches, and aerospace), military, building and construction industries (ceiling paneling, partition boards), packaging etc. Randomly directed fibres were employed in the formation of these natural fibre composites. Later, these natural fibres were given surface treatment with alkaline solutions, to prove their worth in advanced mechanical applications [2-4].

This trend developed, and led to the reinforcement of fibres in the form of laminates. These laminated composites showed significant properties in comparison with random oriented composites. Later, in the life cycle of the composite material, appeared a new form of composite, wherein the fibre is reinforced with a metal, so as to inherit special properties in order that it can be used in the aerospace industry. A Fibre Metal Laminate (FML) was originally developed at the Delft University of Technology. It consisted of thin sheets of aluminium, bonded with fibre adhesive layers. This laminated structure behaves much the same as a simple metal structure, but with considerable specific advantages with regard to properties, such as metal fatigue, impact, corrosion resistance, fire resistance, weight savings and specialized strength properties. Some of the commercially available FMLs such as GLARE (GLAss Reinforced Epoxy laminate), ARALL (Aramid Reinforced ALuminium Laminate) and HTCL (Hybrid Titanium Composite Laminate) have significant properties that are useful in the aviation field [5-6].

Asundi. A, et al [7] investigate fibre metal laminates with respect to the splicing concept. The splicing concept offers benefit for a regular FML panel except for wider panels. This increased width capability can result in a significant reduction in manufacturing cost. Sinke J, et al [8] investigate the detailed behaviour of a fibre layer to have a better understanding of its failure mode. Summerscales J. et al [9] investigate the mechanical properties of an orthotropic composite material which has nine interdependent elastic constants: three Young's modulli, three shear modulli and three Poisson's ratios. Sugun B.S, et al [10] try to find an improved process for the manufacture of fibre metal laminates. This work outlines a simple, cost effective and widely adaptable process for the manufacture of fibre metal laminates. Here, the metal surface is roughened with grit blasting for effecting strong bond between metal and fibre cloth adhesive layers (prepreg). Xun Xu, et al [11] consider natural fibres such as sisal, flax, jute and wood-fibres which possess good reinforcing capability when properly compounded with polymers.

So far, studies have been made on FMLs such as GLARE, ARALL, HTCL and also on FMLs, manufactured with man-made fibres reinforced with other metals, such as magnesium and titanium [12-14], in aeronautical applications. According to Cortes et al, FMLs are capable of absorbing significant energy through localized fibre fracture and shear failure in the metal plies [13]. Also the interface bonding between the composite and the metal plies, tensile behaviour and low velocity impact studies were performed on these FMLs [14]. To bring down the cost of fibres such as carbon and glass, and for the sake of a pollution-free environment, an attempt is made in this work by bringing in a natural fibre, Jute, a cost effective and eco-friendly fibre, into the FML.

Jute is a lingo-cellulosic fibre that falls into the bast fibre category like kenef, hemp, flax, ramie etc. It belongs to the family of Sparrmanniaceae. It requires plain alluvial soil with standing water, moderate warm and wet climate with temperatures ranging from 20°C to 40°C and relative humidity of 70% to 80%, for successful cultivation. This fibre has been an integral part of the culture of Bengal, Bangladesh and some portions of West Bengal. It is called the "Golden Fibre of Bangladesh". It has entered into many diverse sectors of industries, where natural fibres are gradually becoming better substitutes. Its production is concentrated in India and Bangladesh, mainly in Bengal. India is the world's largest jute growing country, with a production of 1,200,600 tonnes per year (during 2011), next to Bangladesh [15]. It is a 100% bio-degradable, recyclable, and thus environment friendly fibre.

Table 1. Properties of Metals and Jute fibre used in FML

Property	Aluminium	Magnesium	Jute Fibre
Density (Kg/m^3)	2800	1770	1460
Tensile Strength (MPa)	248-483	290	393-773
Young's Modulus (GPa)	69	45	13-26.5
Elongation (%)	40	1.5	1.16-1.8

In the present work, an attempt is made for the first time, to replace a portion of carbon fibre with natural fibre jute. Also the influence of alternate metal, magnesium on the mechanical performance of the FML is studied. The idea of utilizing magnesium metal in place of aluminium has arisen due to its capturing property, low density. It is notable that magnesium is 1.55 times lighter than aluminium and hence it results in reduction in weight of the existing FMLs. The resulting FMLs are named as CAJRALL (CArbon-Jute Reinforced ALuminium Laminate) and CAJRMAL (CArbon-Jute Reinforced MAgnesium Laminate). The behaviour of CAJRALL and CAJRMAL are examined when they are subjected to tensile, flexure and impact tests. Their experimental findings are validated with FE simulation. Moreover, theoretical evaluation of the tensile parameters is executed and these are compared with experimental and simulated results. Also micro level examination of the CAJRMAL is performed for the axially and impact loaded specimens to analyse their pattern of failure. The mechanical properties of the metals and the jute fibre are listed in the Table 1.

2. Materials and FML fabrication

2.1. Materials used for laminate preparation

The materials utilized for the preparation of the FML samples are carbon (300 gsm) and jute (200 gsm) fibres, aluminium 2024 T3 sheet with thickness of 0.19 mm, magnesium AZ31 sheet with thickness 0.25 mm, epoxy resin of grade LY 556 and Araldite hardener of grade HY 951.

2.2. CAJRALL and CAJRMAL manufacture

The laminate to be tested for different behaviors such as tensile, flexure and impact are prepared with varying stacking orders of fibres and metal based on the direction of loading. The CAJRALL specimens considered for tensile test are oriented with stacking sequences of (Al/Ca$_{0^\circ}$/Al/Ju$_{0^\circ}$/Ju$_{90^\circ}$/Al/Ca$_{0^\circ}$/Al) and (Al/ Ca$_{0^\circ}$/Al/Ju$_{0^\circ}$/Ju$_{90^\circ}$/Al/Ca$_{90^\circ}$)$_S$. The CAJRALL specimens to be subjected to Flexure test are stacked in the orders of (Ca$_{0^\circ}$/Al/ Ca$_{0^\circ}$/Ju$_{0^\circ}$/Ju$_{90^\circ}$/Ca$_{0^\circ}$/Al/Ca$_{0^\circ}$) and (Ca$_{0^\circ}$/Al/ Ca$_{0^\circ}$/Al/Ju$_{0^\circ}$/Ju$_{90^\circ}$/Al/Ca$_{0^\circ}$/Al/Ca$_{0^\circ}$). Here the carbon fibre is placed in the top and bottom layers of the laminate, as it has high bending resistance when compared to other materials in the laminate. The specimens for Impact test are arranged in quasi-isotropic stacking sequence of (Ca$_{0^\circ}$/Al/Ca$_{45^\circ}$/Al/Ju$_{0^\circ}$/Ju$_{90^\circ}$/Al/Ca$_{-45^\circ}$/Al/Ca$_{0^\circ}$/Al/Ca$_{-45^\circ}$/Al/Ju$_{0^\circ}$/Ju$_{90^\circ}$/Al/Ca$_{-45^\circ}$) and a varying sequence of (Ca$_{0^\circ}$/Al/Ca$_{90^\circ}$/Al/Ju$_{0^\circ}$/Ju$_{90^\circ}$/Al/Ca$_{90^\circ}$Al/Ca$_{0^\circ}$/Al/Ca$_{90^\circ}$/Al/Ju$_{0^\circ}$/Ju$_{90^\circ}$/Al/Ca$_{90^\circ}$/Al). The CAJRMAL specimens are prepared by just replacing the Aluminium by Magnesium in the above mentioned stacked laminates. The laminates arranged as above are blended with epoxy resin through hand lay-up technique. Then they are cured at room temperature and compressed for ten minutes in the compression molding machine at a pressure of 70 kg cm^{-2} and at temperature of 70 °C and thus the final FML is obtained.

3. FML response under axial, bending and impact loadings

3.1 Axial loading

The CAJRALL and CAJRMAL specimens fabricated as above for the tensile test are cut and tested according to ASTM D 3039 standard in the INSTRON 3369 Universal Testing Machine and the test findings are shown in Fig. 1. (a) and (b).

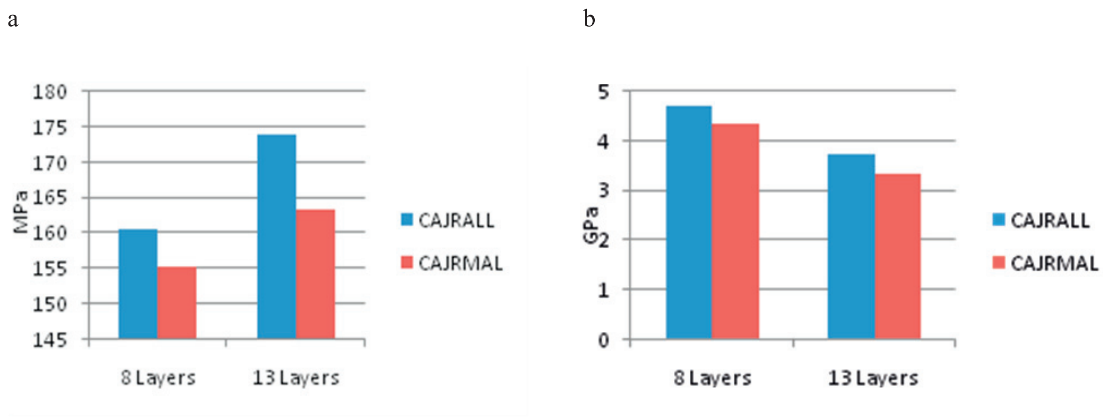

Fig. 1. Plot of (a) Tensile strength and (b) Young’s Modulus for CAJRALL and CAJRMAL specimens.

3.2 Flexure loading

The CAJRALL and CAJRMAL specimens fabricated as above for the flexure test are cut and tested according to ASTM D790 standard in the three point bending test set-up and the test findings are given in Fig. 2. (a) and (b).

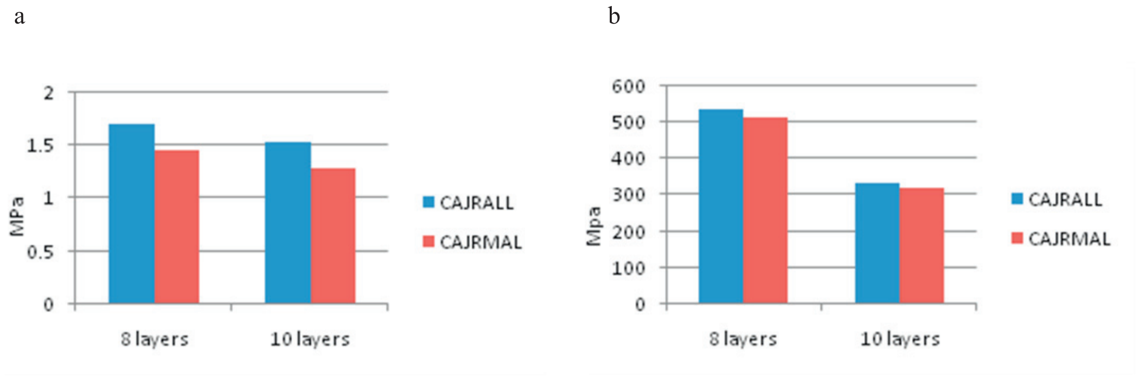

Fig. 2. Illustration of (a) Bending strength and (b) Flexure Modulus for CAJRALL and CAJRMAL specimens.

3.3 Impact loading

The CAJRALL and CAJRMAL specimens fabricated as above for the impact test are cut and tested according to ASTM D 7136 standard in the Izod impact test set-up and the test findings are shown in Fig. 3.

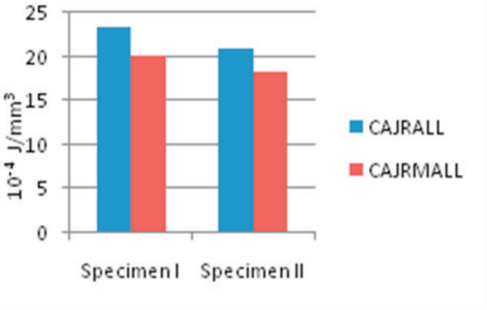

Fig. 3. Plot of Impact Toughness for CAJRALL and CAJRMAL specimens.

3.4 Tensile properties of individual plies in CAJRALL and CAJRMAL laminates

To determine theoretical values of stress in individual layers of carbon, jute, aluminium, magnesium and also in the total laminate as well as for the execution of Finite Element Analysis of the FMLs, the tensile parameters of the FMLs such as Young's Modulus, Poisson's ratio are required. These parameters are evaluated for carbon-epoxy and jute epoxy laminates, with carbon and jute fibres oriented separately in 0° and 90° directions and are tabulated in Table 2. The stress values in the individual layers obtained using stress-strain relation and equations (1) and (2), are outlined in Fig. 4. (a) and (b).

Table 2. Tensile properties of individual plies in CAJRALL

Property	Carbon 0°	Carbon 90°	Jute 0°	Jute 90°
E_{11}(GPa)	166.8	193.6	10.69	13.01
E_{12}(GPa)	5.2	7.724	34.03	10.10
μ_{11}	0.465	0.336	0.318	0.3227
μ_{12}	0.09	0.0399	0.103	0.249
G (GPa)	12.23	12.23	2.15	4.44

The strain matrix is given by

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = [\mathrm{A}]^{-1}[\mathrm{N}] \ \mathrm{N}/mm^2 \tag{1}$$

where **[A]** = $\sum$ [Q] × t, is the extensional stiffness matrix, t is the thickness of the laminate and $[Q]$ is the reduced stiffness matrix.

$$[\mathrm{N}] = \begin{bmatrix} \mathrm{N}_x \\ \mathrm{N}_y \\ \mathrm{N}_{xy} \end{bmatrix} \mathrm{N}/mm \tag{2}$$

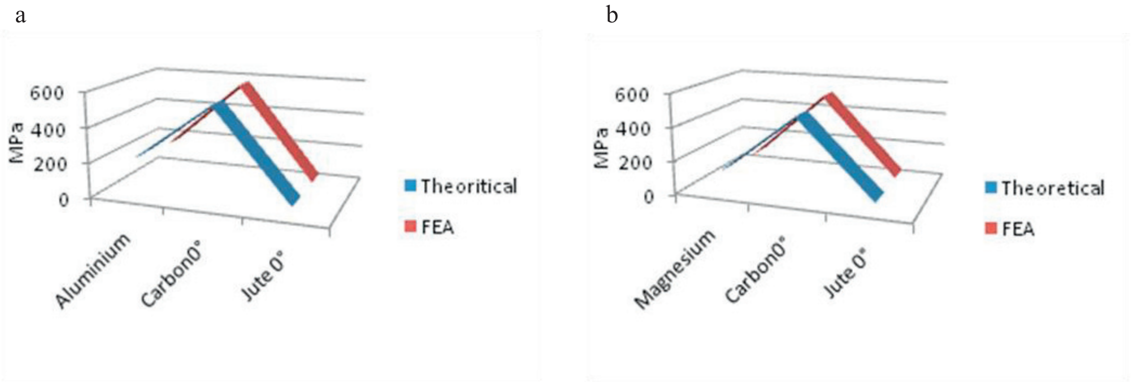

Fig. 4. Comparison of axial stress values (a) CAJRALL and (b) CAJRMAL.

4. Analysis using FEM

The CAJRALL and CAJRMAL specimens are modelled in ANSYS and ABACUS softwares to simulate tensile and flexure performances. The results of tensile analysis of CAJRALL and CAJRMAL are shown in Fig. 5. (a) and (b) respectively. The tensile stress for 8 layered and 13 layered CAJRMAL specimens are found to be 168.21 MPa and 184.6 MPa respectively and that of CAJRALL are 158 MPa and 194 MPa respectively. On the other hand, the bending resistances of the 8 layered and 10 layered CAJRMAL specimens are found to be 502.4 MPa and 301.6 MPa respectively and that of CAJRALL are 525 MPa and 315 MPa respectively.

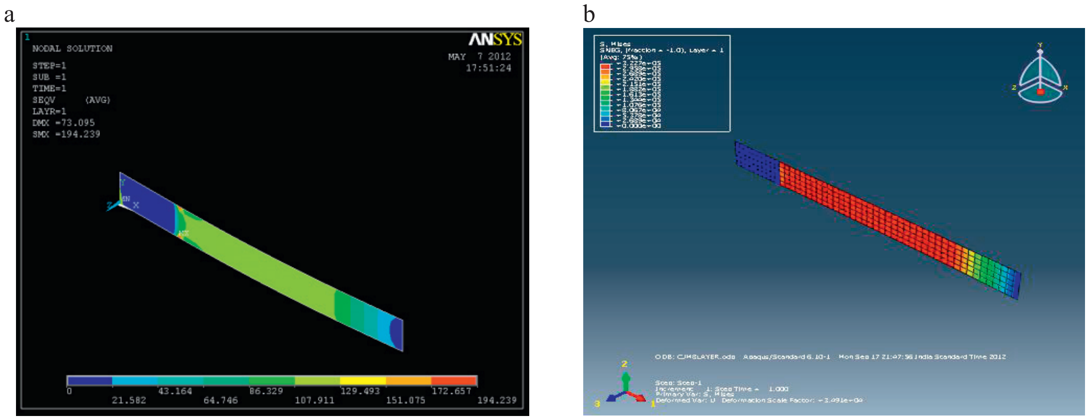

Fig. 5. Illustration of FEM analysis of Axial loading of (a) CAJRALL and (b) CAJRMAL.

5. Results and Discussion

Fig. 1. (a) and (b) shows the experimental results of axially loaded CAJRALL and CAJRMAL specimens. The tensile stress for 8 and 10 layered CAJRALL are found to be 160.5 MPa and 170.4 MPa respectively and that of CAJRMAL are 155.3 MPa and 163.5 MPa respectively. On similar lines, the Young's modulus of the 8 and 10 layered CAJRALL are obtained as 4.71 GPa and 3.74 GPa respectively and that of CAJRMAL are 4.35 GPa and 3.3 GPa respectively. The results obtained when subjecting the CAJRALL and CAJRMAL specimens to bending are illustrated in Fig. 2. (a) and (b). The flexure strength of the 8 and 10 layered CAJRALL are found to be 537.5 MPa and 334.2 MPa respectively and that of CAJRMAL are 515.3 MPa and 318.5 MPa respectively. Further the flexure modulus of the 8 and 10 layered CAJRALL are observed as 1.71 MPa and 1.54 MPa respectively and that of CAJRMAL are 1.45 MPa and 1.29 MPa respectively. Fig. 3. demonstrates the results of impact loaded CAJRALL and CAJRMAL specimens. The resulting impact toughness of the quasi-isotropic oriented CAJRALL and CAJRMAL specimens are 23.42 x10^{-4} J/mm^3 and 20.95 x10^{-4} J/mm^3 respectively and that of generally stacked CAJRALL and CAJRMAL specimens are 20.04 x10^{-4} J/mm^3 and 18.22 x10^{-4} J/mm^3 respectively.

From Fig. 1.(a) and (b), it is seen that the tensile strength of the CAJRALL and CAJRMAL materials increase with increase in the number of layers whereas their Young's moduli decrease with the number of layers. Moreover, as the number of layers increase, the flexure resistance of the CAJRALL and CAJRMAL materials decrease and this is evident from Fig. 2. (a) and (b). It can be viewed from Fig. 3 that the impact toughness of the CAJRALL and CAJRMAL materials has a decreasing trend for Specimen II when compared to Specimen I. Further, it may be noted that the experiment results of the FMLs closely match with the analytical and theoretical results with a maximum variation of 11% and 13 % respectively for CAJRALL and 12% and 9% for CAJRMAL specimens.

5.1 Microstructure Analysis for characterization of damage in the CAJRMAL specimens

In order to characterize the fracture surface of the various CAJRMAL samples, microstructure analysis is carried out using Scanning Electron Microscope (SEM). It is observed from Fig. 6. (a) and (b), the failure of the axially loaded CAJRMAL specimens are mostly due to jute fibre elongation and pull out. Also it can be mentioned that tensile specimens are prone to delamination i.e., detachment of layers from each other, which leads to failure. The impact damage mechanism in the CAJRMAL laminate constitutes a very complex process. It is a combination of matrix cracking, surface buckling, delamination, fiber shear out/ pull out and fiber fracture, as illustrated in Fig. 7. (a) and (b), that usually interact with each other. The sequence of failure of CAJRMAL specimen is noted with the start of matrix cracking, then failure of the jute fibre, delamination, carbon fracture and finally magnesium ductile elongation and fracture.

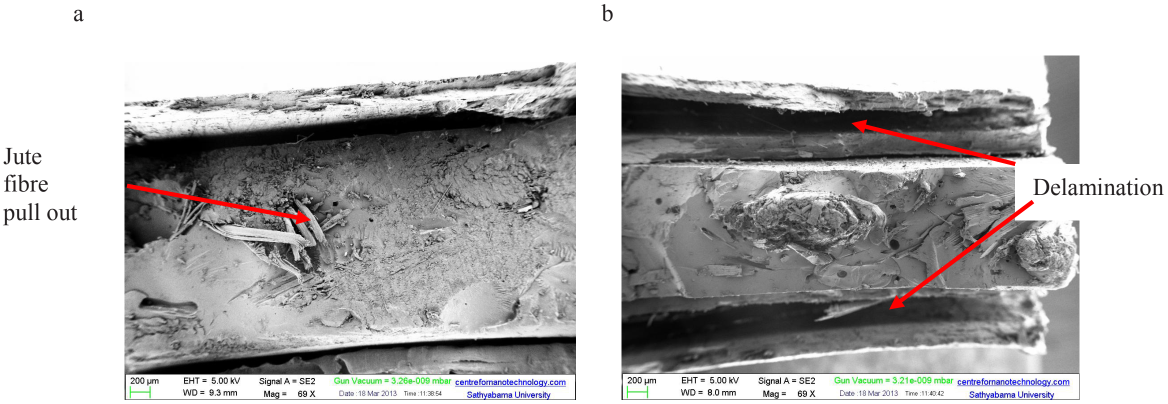

Fig. 6. SEM images of axially loaded, fractured CAJRMAL specimens (a) Fibre pull out and (b) Delamination between layers.

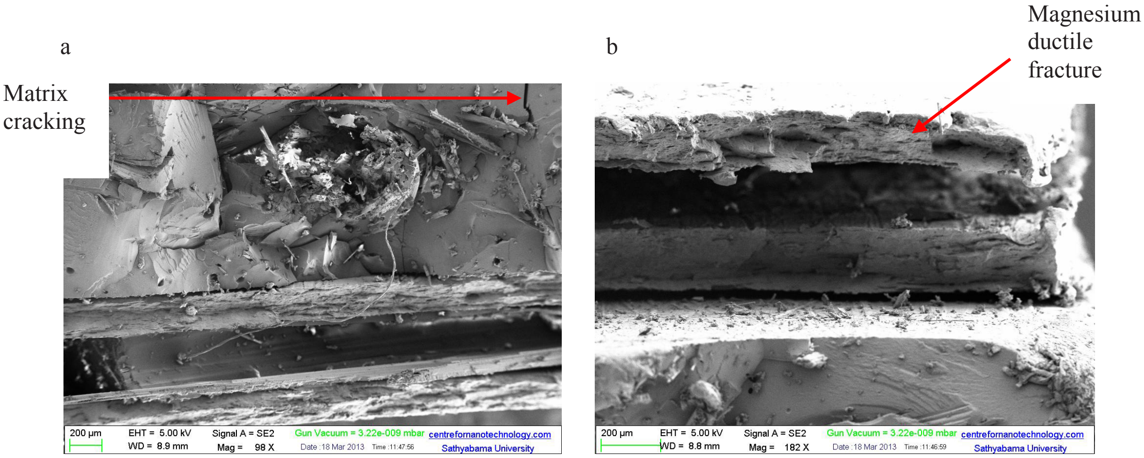

Fig. 7. SEM photographs of fractured CAJRMAL specimens under impact loading (a) Matrix cracking and (b) Ductile elongation of magnesium

6. Conclusions

In the present work, in CArbon Reinforced ALuminium Laminate (CARALL), a portion of carbon fibre is replaced by natural fibre jute, owing to the high cost of carbon and to provide pollution-free environment and its mechanical performance is analysed. Also, owing to low weight property of the FMLs, an attempt is made in CAJRALL, by replacing aluminium with magnesium metal. It is observed that the tensile and flexure stresses of CAJRALL and CAJRMAL are directly proportional and the Flexure modulus is inversely proportional to the number of layers. Moreover, the CAJRALL with $(Ca_{0°}/Al/Ca_{45°}/Al/Ju_{0°}/Ju_{90°}/Al/Ca_{-45°}/Al/Ca_{0°}/Al/Ca_{-45°}/Al/Ju_{0°}/Ju_{90°}/Al/\ Ca_{-45°})$ arrangement and CAJRMAL with the same arrangement but replaced with magnesium metal have better impact resistance. Also the experiment findings are in close agreement with analytical and theoretical results with a maximum variation of about 11% and 13% for CAJRALL and 12% and 9% for CAJRMAL FMLs respectively. The microstructure study reveals that the predominant failure mechanisms in axially loaded CAJRMAL specimen are found to be fibre pull out and delamination between layers and in impact loaded specimens, it is matrix cracking. Since magnesium is 1.55 times less heavy than aluminium and also not much difference is observed from the results of the mechanical response of CAJRMAL, it is evident that, it is beneficial to use CAJRMAL in place of CAJRALL in applications that essentially require low weight materials.

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